Proceeding Paper

The structure of blizzard transport and heat losses of sublimation of ice crystals in blizzards on the surface of the Elbrus Mountain glacier†

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Abstract: Automated meteorological measurements on the Garabashi glacier during the accumulation season in February 2020 and February 2022 were organized. For the first time for glaciers of the Central Caucasus, the estimates of snowdrift transport based on automated measurements with high time discreteness were performed and a numerical algorithm of crystal sublimation rate during blizzards was applied. It has been shown that the sublimation of crystals could be comparable with sensible and latent heat fluxes and during night blizzards could be the main component of surface heat balance. Also, the method of measuring of the vertical blizzard transport distribution using "snowdrift traps" was tested. In cases of general blizzards, the "inversions" of vertical distribution were noticed.

Keywords: Mountain glaciers; sublimation of ice crystals; blizzards; snowdrift transport; Elbrus Mountain

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1. Introduction

The cryosphere is an integral element of the geographic envelope and high mountain regions. Mountain glaciers are only 1% on a total planet's ice cover, but they significantly affect the regional climate (especially the hydrological regime) and at the same time are one of the key indicators of regional and global climate change [1]. Mountain glaciers are characterized by significant degradation rates, losing on average 1–2% of their mass per year under the conditions of global warming [2]. The process of deglaciation has a negative impact on agriculture and recreational activities, leads to an increase in the level of the World Ocean, damages infrastructure and disrupts the ecological balance in mountainous regions [3]. Therefore, the physical and mathematical description of mountain glaciation, including within the framework of global climate models, is an urgent task for the Earth sciences. The implementation of this task is impossible without meteorological measurements on mountain glaciers, which will make it possible to carry out quantitative estimates of the mass balance components of a mountain glacier: the layer of annual melting (ablation) and snow accumulation.

The snow accumulation on a mountain glacier's surface is significantly affected by windy snow transport and ice crystals sublimation during blizzards [4]. The snow mass losses due to sublimation can be significant: in different regions, this value varies within 10-20% [5] and has a significant impact on the mass balance of mountain glaciers, and ultimately on river runoff. Therefore, it is necessary to take this process into account for modeling mountain glaciers and runoff in numerical weather and climate models.

2. Materials and methods

2.1. Meteorological measurments

A complex of meteorological and actinometric measurements on the Garabashi glacier (Figure 1) was carried out in accumulation season from January 28 to February 5, 2020 and January 27 to February 24, 2022. The meteorological site 20x20 m in size was the snow surface of the southern slope of Mount Elbrus at an altitude of 3890 m above sea level.

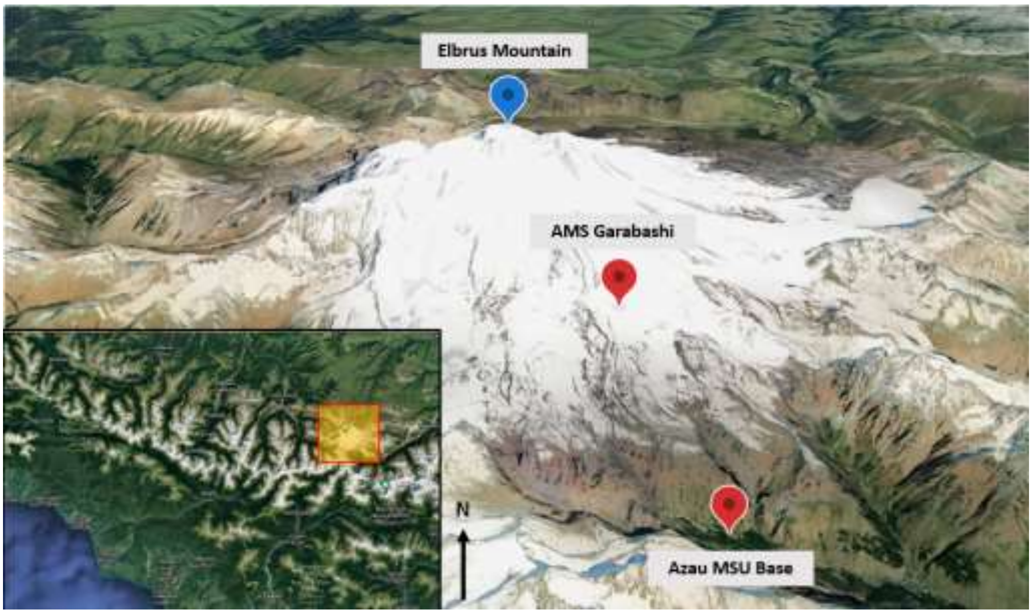


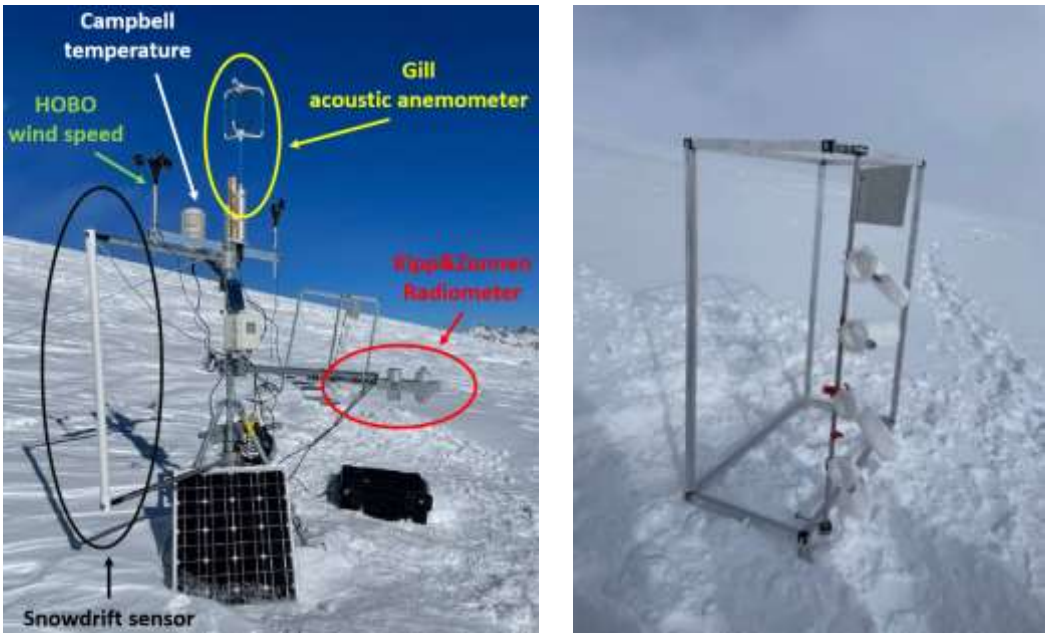
Figure 1. Location of the expedition and measurements (illustration from Google Earth).

Meteorological measurements on the Garabashi glacier were carried out in an automated mode with a discreteness of 1 minute (Figure 2a). The following parameters were measured:

- Air temperature and relative humidity at heights of 0.55 and 2 m above the surface (using HOBO and Campbell weather stations);
- Wind speed and direction with HOBO anemometers;
- Incoming and reflected short-wave radiation, thermal radiation of the atmosphere and snow surface at a level of 1 m using Kipp&Zonnen CNR1 net radiometer;
- Snowdrift transport intensity according to the ISAW FlowCapt4 7 acoustic snowdrift sensor.

In addition, daily observations were carried out on five snow gauges located at a distance of 20 m in various conditions of snow accumulation, as well as measurements of snow drift by weighing "snowdrift traps" at levels 38, 65, 90 and 115 cm above the surface (Figure 2b).

Moreover, in 2020 high-frequency (20 Hz) recording of three components of wind speed at a height of 2 meters was carried out using a Gill Windmaster acoustic anemometer.



(**a**) (**b**)

Figure 2. (**a**) Meteorological complex on the Garabashi glacier; (**b**) "Snowdrift traps".

2.2. Calculating methods of the surface heat balance components and ice crystals sublimation rate

The complete heat balance equation for the snow cover in the high-altitude area during the accumulation season can be written in a general form:

$$Q_m = R + H + LE + Q_D, \tag{1}$$

where Q_m is heat consumption for ice melting, R is the radiation balance, H is the turbulent sensible heat flux, LE is the turbulent latent heat flux, Q_D is the heat flux due to molecular diffusion in snow. The components of equation (1) have been evaluated in many studies for various mountain glaciers of the Earth. Estimates made for the Caucasian Dzhankuat glacier [6] showed that the contribution of the radiation component to melting in the ablation region is 70-80%, the turbulent heat flow is 20-30%, however, the LE value can be both positive and negative.

Measurements carried out on the Garabashi glacier in both years made it possible to apply the method of aerodynamic formulas (the bulk formula method) to calculate sensible and latent heat fluxes over the snowy surface. This method is most often used to estimate turbulent fluxes over glaciers [7]. In general, sensible and latent heat fluxes, according to this method, are expressed as follows:

$$H = C_p K \rho (T - T_0);\ LE = LK\rho(q - q_0). \tag{2}$$

Here L is the specific heat of evaporation–condensation, J/kg; ρ is air density, kg/m³; C_p is the specific heat of air. Thus, to restore sensible and latent heat fluxes, only information about the temperature and specific humidity of the air at a height of 2m (T, q) and at the surface (T_0, q_0) obtained according to HOBO and Campbell is needed. In this case, the coefficient of turbulent heat transfer K is determined through the function of the Richardson volume number Ri_b according to [8]:

$$K = \frac{\varkappa^2 u}{(\ln {}^{z_2}/_{z_0})^2} f(Ri_b);\ f(Ri_b) = \begin{cases} (1 - 5Ri_b)^2, Ri_b > 0, \\ (1 - 16Ri_b)^{0,75}, Ri_b < 0, \end{cases} \text{ where } Ri_b = \frac{g}{T} \frac{{}^{dT}/_{dz}}{({}^{du}/_{dz})^2}, \tag{3}$$

z_0 is the dynamic roughness parameter set for the glacier surface equal to 10^{-3}m; $\varkappa$=0.4 is the von Karman constant; g is the acceleration of gravity, m/s²; u is the wind speed at the level of z_2 = 2m.

Earlier for the ablation season it was shown that the eddy covariance method can be considered as a "reference" one [6]. Therefore, the data of acoustic anemometer Gill of 2020 was carried out in accordance with algorithms described in [9].

At the same time, complete evaporation from the snow surface includes not only a turbulent flux of moisture, but also the sublimation of ice crystals. Studies show that during intensive blizzards with wind speeds more than 10 m/s, sublimation can have a contribution comparable to the sensible and latent heat fluxes [10]. The sublimation rate is determined by the degree of turbulence of the atmosphere in the surface layer, the criterion of which is the Reynolds number and in a blizzard at a given altitude is calculated as [10]:

$$S(z) = -\sum_r M_r \frac{\partial}{\partial r}\left[\frac{n_r}{4\pi r^2 \rho_p}\left(\frac{\partial m}{\partial t}\right)_r\right], \qquad \text{where} \quad \left(\frac{\partial m}{\partial t}\right)_r = \frac{2\pi r\left(\frac{q}{q_s}-1\right)}{\frac{\lambda_s}{k_T T Nu}\frac{1}{}\left(\frac{\lambda_s M_w}{R_g T}\right)+\frac{1}{k_\upsilon q \rho_f Sh}}. \tag{4}$$

The key value is the rate of mass change of the sublimating particle $\partial m/\partial t$, which takes into account the degree of atmospheric turbulence in the surface layer, as well as the ratio of the intensity of turbulent heat transfer and molecular diffusion during heat and mass transfer. This value can be determined through the measured values of temperature and specific humidity of the air, as well as by the standard deviation of the wind speed. The mass M_r and the number n_r of particles with radius r and density ρ_p are calculated using a continuous particle size distribution based on the total mass M of snow particles measured by the ISAW FlowCapt snowdrift sensor. For calculations, the radius r is usually selected in the range of 0-600 microns in increments of 10 microns.

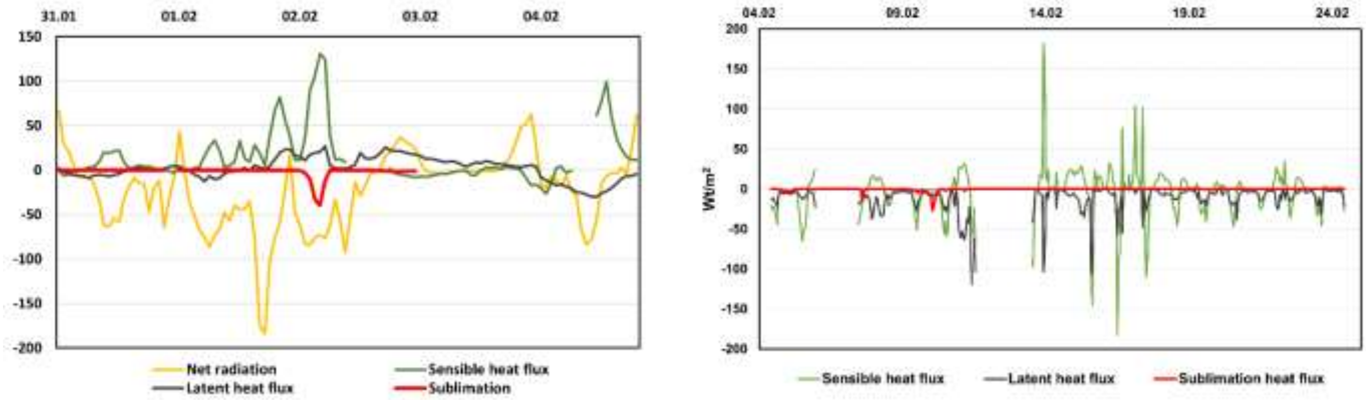
3. Results and discussion

3.1. Estimates of heat balance components

Using calculation methods that were described previously, the time series of sensible and latent heat fluxes and heat losses for sublimation of ice crystals in blizzards were obtained for the periods from 31 January to 5 February 2020 (6 days) and 4 to 24 February 2022 (20 days).

As shown at Figure 2b the maximum values of sensible heat fluxes into the atmosphere in 2022 were obtained on the night of the 14th of February (180 W/m²), from the atmosphere - at noon of 16th (180 W/m²). The maximum latent heat flux was also observed on the night of the 14th of February (150 W/m²). At the same time in 2020 (Figure 2a) the values of turbulent heat fluxes didn't exceed 130 W/m².

It's noticeable that the heat losses for ice crystals sublimation during blizzards can reach 30 W/m². Such results were obtained for the daytime blizzard on February 2, 2020 (30 W/m²) and the night blizzard on February 10, 2022 (27 W/m²). In the case of a daytime blizzard, the heat costs for sublimation turned out to be less significant compared to the turbulent heat fluxes and the net radiation. However, during the night blizzard on February 10, 2022, the heat costs for sublimation more than doubled the estimates of turbulent fluxes of sensible and latent heat. It should be noted that the observation period was characterized by predominantly uniform and slightly cloudy weather, in which the heat losses for sublimation are close to zero. However, under conditions of night blizzards, heat consumption for sublimation can become a determining component of the heat balance.



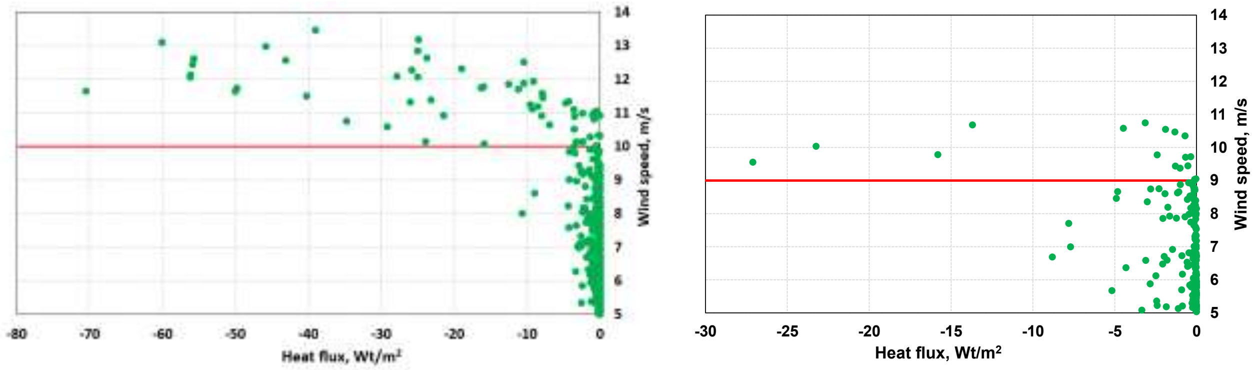
(**a**) (**b**)

Figure 3. Time series of components of surface heat balance in 2020 (**a**) and in 2022 (**b**).

At the same time, the intensity of ice crystals sublimation is largely determined by the near-surface wind speed (Figure 4). At speeds less than 4 m/s, sublimation is practically not observed and becomes significant at speeds above 9 m/s. The maximum heat loss due to sublimation is observed at a wind speed about 10-12 m/s. At higher speeds, a decrease in the intensity of sublimation is observed, which is associated with a decrease in the specific moisture content and temperature.

In 2020 the heat losses for sublimation were estimated with 5 minutes averaging. The maximum momentum effect of sublimation was observed on February 2 during the strongest snowstorm. The process reached the highest intensity at speeds more than 10 m/s with values up to 70 W/m² (Figure 4a), which is comparable with the main components of the heat balance. However, at the same 10 m/s, values less than 10 W/m² were revealed, which is due to a small moisture deficit and a small temperature difference "crystal – ambient air". The same results were obtained for 2022 with hourly data averaging. Therefore, we can say that significant wind speeds are a necessary but not sufficient factor in the development of the sublimation process during blizzards.

In addition, the sublimation of ice crystals plays a significant role in the total evaporation and snow mass losses on the surface. The calculation of the rate of this process makes it possible to separate the corresponding component from the moisture flow due to the sublimation of water vapor from the surface of the snow cover. Thus, in strong snowstorms, for a reliable assessment of the heat balance and mass balance of the glacier surface, it is necessary to take into account the process of sublimation of ice crystals.



(**a**) (**b**)

Figure 4. Dependence of heat losses due ice crystals sublimation from near-surface wind speed for 2020 with 5 minutes averaging (**a**) and 2022 with 1 hour averaging (**b**).

3.2. Estimates of snowdrift transport

During the expedition of 2022 using the ISAW FlowCapt FC4 acoustic snowdrift sensor, data on the flow of ice particles were obtained. Moreover, the vertical distribution of snow at four levels (38, 65, 90 and 115 cm above the surface) was assessed using "snowdrift traps". Based on these data, as well as a general analysis of the synoptic situation, the periods with observed blizzards were classified according to [4] into cases of ground (February 6) and general blizzards (February 4-5, February 6-7, February 9-11, 13 and 19 February).

Intense precipitation on February 10, due to the frontal system of the southern cyclone, made the greatest contribution to the dynamics of snow accumulation. The period from February 10 to February 11 was classified as a general blizzard. But the value of transfer per amounted only 0.7% of the integral value for the expedition period (253 kg /m^2).

The most intense snow transfer during the entire expedition was observed on February 6 and was caused by a ground blizzard. Wind gusts according to the snowdrift sensor reached 35-40 m/s, the average speed was about 20 m/s (Figure 5b). Apparently, such high wind speeds were observed due to a downslope windstorm [11, 12]. The occurrence of this phenomenon was facilitated by northwestern flows in the high-altitude frontal zone at a high inflow velocity. The intensity of snow transport reached 76 g/m^2/s (Figure 5a), and the integral value of the snowdrift on February 6 was 162 kg/m^2 (69% of the total value for the expedition period).

(a)

(b)

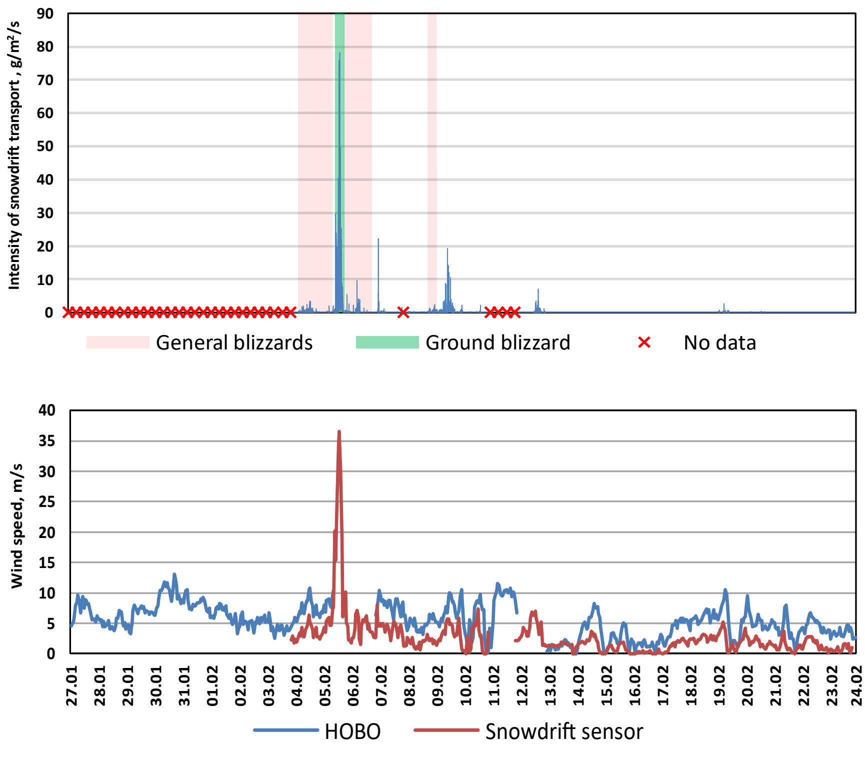


Figure 5. (**a**) Time series of snowdrift intensity, g/m^2/s, according to acoustic snowdrift sensor data; (**b**) Time series of wind speed according to the HOBO weather station and acoustic snowdrift sensor.

As noted in [13], horizontal snow transport decreases exponentially with height. The observational data (Figure 6) generally correspond to this distribution: normally, more snow was collected in traps located closer to the snow cover surface than in the upper ones. Thus, on February 10 during snowfall the wind speed varied in the range of 5–10 m/s, which, according to [4], is sufficient for deflation to occur. Thus, the filling of the lower trap occurred faster than that located above it.

However, there were cases with "inversions" when a large mass of snow accumulated in “snowdrift traps” located higher from the surface. On February 9, precipitation was observed throughout the day with a wind speed of about 3-7 m/s. Such conditions favored the emergence of a general blizzard. Due to the small deflationary component and the relatively low wind speed, the filling of the upper traps was more intense, because the wind speed increased with altitude (in Figure 5b, the wind speed at the level of the snowdrift sensor located below the AMS HOBO sensor is characterized by lower values).

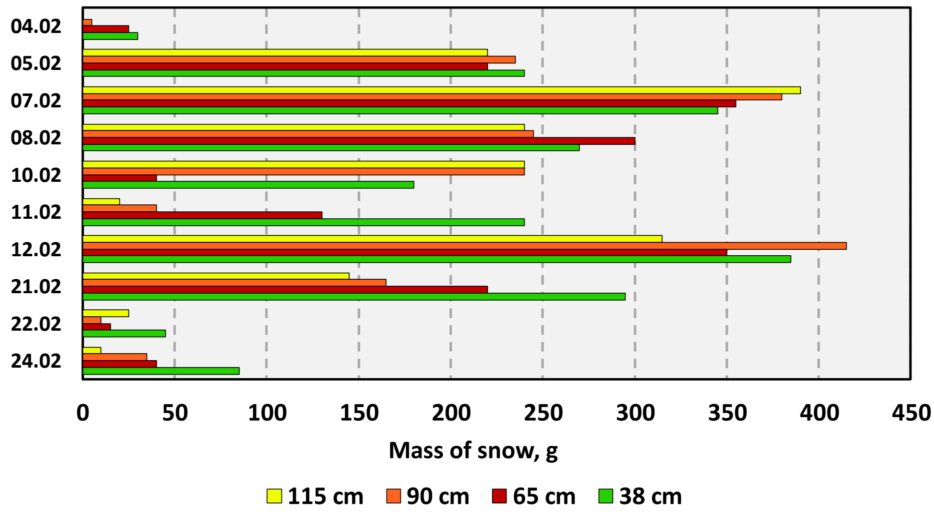


Figure 6. Histogram of the vertical distribution of snowdrift transport over “snowdrift traps”.

4. Conclusions

The measurement data obtained during two expeditions was analysed. It made possible to develop knowledge about snow transport’s quantitative characteristics on Elbrus Mountain, as well as to estimate the magnitude of heat balance components for Garabashi glacier in winter conditions.

It has been shown that the amount of heat consumption for sublimation during snowstorms reaches 70 W/m^2, that is comparable with the other heat balance components. We’ve shown that a process becomes physically significant if the wind speed more 10 m/s. During night blizzards, this value may exceed the other components of the heat balance. Therefore, taking into account the process of sublimation of ice crystals when calculating the surface heat balance and the mass balance of a mountain glacier is urgently needed.

Moreover, periods with low and general blizzards were identified. The blowing snow period was characterized by high wind speeds (gusts of 35–40 m/s), which was probably associated with a downslope windstorm [10,11]. For the first time, a method of measuring integral snowdrift transport was tested using “snowdrift traps” installed at four levels. It was shown that an exponential decrease in the intensity of horizontal snow transport with height is characteristic of deflationary blizzards. At the same time, in cases of general blizzards, the effect of an increase in wind speed with height prevails, and cases of “inversion” vertical distribution occur. However, this method of measurement should be verified and may be revised, due to the unknown reliability of the data obtained.

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